## Classification of Amplifiers

<table>
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<tr>
<th>Type of Signal</th>
<th>Based on No.of Stages</th>
<th>Type of Configuration</th>
<th>Classification based on conduction angle</th>
<th>Frequency of Operation</th>
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<tr>
<td>Small Signal</td>
<td>Single Stage</td>
<td>Common Emitter</td>
<td>Class A Amplifier</td>
<td>Direct Current (DC)</td>
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<td>Large Signal</td>
<td>Multistage</td>
<td>Common Base</td>
<td>Class B Amplifier</td>
<td>Audio Frequencies (AF)</td>
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<td></td>
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<td>Common Collector</td>
<td>Class AB Amplifier</td>
<td>Radio Frequencies (RF)</td>
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<td>Class C Amplifier</td>
<td>VHF, UHF and SHF Frequencies</td>
</tr>
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</table>
**Different Regions Of Operation**

<table>
<thead>
<tr>
<th>Region of Operation</th>
<th>Emitter Base Junction</th>
<th>Collector Base Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut off</td>
<td>Reverse biased</td>
<td>Reverse biased</td>
</tr>
<tr>
<td>Active</td>
<td>Forward biased</td>
<td>Reverse biased</td>
</tr>
<tr>
<td>Saturation</td>
<td>Forward biased</td>
<td>Forward biased</td>
</tr>
</tbody>
</table>
Transistor Voltage specifications For Various Operating Regions

<table>
<thead>
<tr>
<th>Transistor</th>
<th>$V_{CE}$(sat)</th>
<th>$V_{BE}$(sat)</th>
<th>$V_{BE}$(active)</th>
<th>$V_{BE}$(cut-in)</th>
<th>$V_{BE}$(cut-off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.2 V</td>
<td>0.8 V</td>
<td>0.7 V</td>
<td>0.5 V</td>
<td>0 V</td>
</tr>
<tr>
<td>Ge</td>
<td>0.1 V</td>
<td>0.3 V</td>
<td>0.2 V</td>
<td>0.1 V</td>
<td>0 V</td>
</tr>
</tbody>
</table>

Condition for Active & Saturation Regions

For saturation: $I_B > \frac{I_C}{\beta_{dc}}$

For active region: $V_{CE} > V_{CE}$(sat)
Operating point near saturation region gives clipping at the positive peaks

Operating point near cut-off region gives clipping at the negative peaks

Operating point at the centre of active region is most suitable
Transistor Biasing

Fixed bias circuit

Voltage divider bias circuit
CE, CC, & CB Amplifiers

Practical common emitter amplifier circuit

Common collector circuit

Common base circuit
H-Parameters Representation Of An Amplifier

\[ V_i = h_{11} I_i + h_{12} V_o \]
\[ I_o = h_{21} I_i + h_{22} V_o \]

Definitions of h-parameter

The parameters in the above equation are defined as follows:

\[ h_{11} = \left. \frac{V_i}{I_i} \right|_{V_o=0} \] = Input resistance with output short-circuited, in ohms.

\[ h_{12} = \left. \frac{V_i}{V_o} \right|_{I_i=0} \] = Fraction of output voltage at input with input open circuited.

This parameter is ratio of similar quantities, hence unitless.

\[ h_{21} = \left. \frac{I_o}{I_i} \right|_{V_o=0} \] = Forward current transfer ratio or current gain with output short circuited.

This parameter is a ratio of similar quantities, hence unitless.

\[ h_{22} = \left. \frac{I_o}{V_o} \right|_{I_i=0} \] = Output admittance with input open-circuited, in mhos.

a) With output short circuited:

\[ h_{11} = h_i : \text{ Input resistance} \]
\[ h_{21} = h_f : \text{ Short circuit current gain} \]

b) With input open circuited:

\[ h_{12} = h_r : \text{ Reverse voltage transfer ratio} \]
\[ h_{22} = h_o : \text{ Output admittance} \]
Transistor configurations and their hybrid models

CE
\[ V_b = h_{ie} I_b + h_{re} V_c \]
\[ I_c = h_{ie} I_b + h_{oe} V_c \]

CC
\[ V_b = h_{ic} I_b + h_{rc} V_e \]
\[ I_e = h_{ic} I_b + h_{oc} V_e \]

CB
\[ V_e = h_{ib} I_e + h_{rb} V_c \]
\[ I_c = h_{ib} I_e + h_{ob} V_c \]
Small Signal Analysis Of A Junction Transistor

Basic transistor amplifier

Transistor amplifier in its h-parameter model
small-signal analysis of a transistor amplifier

\[ A_i = \frac{-h_f}{1 + h_o R_L} \]

\[ A_{ds} = \frac{A_i R_s}{Z_i + R_s} \]

\[ Z_i = h_i + h_r \]

\[ A_{iR} = h_i - \frac{h_f h_r}{h_o + Y_L} \]

\[ A_v = \frac{A_i R_L}{Z_i} \]

\[ A_{VS} = \frac{A_v R_i}{Z_i + R_s} = \frac{A_i R_L}{Z_i + R_s} = \frac{A_{is} R_L}{R_s} \]

\[ Y_o = h_o - \frac{h_f h_r}{h_i + R_s} = \frac{1}{Z_o} \]

\[ A_p = A_v A_i = A_i^2 \frac{R_L}{Z_i} \]
Guidelines for Analysis of a Transistor Circuit

1. Draw the actual circuit diagram.

2. Replace coupling capacitors and emitter bypass capacitor by short circuit.

3. Replace dc source by a short circuit. In other words, short $V_{CC}$ and ground lines.

4. Mark the points B(base), C(collector), E(emitter) on the circuit diagram and locate these points as the start of the equivalent circuit.

5. Replace the transistor by its h-parameter model.
Design Problem

Consider a single stage CE amplifier with $R_s = 1\ \Omega$, $R_1 = 50\ \Omega$, $R_2 = 2K$, $R_C = 1K$, $R_I = 1.2\ \Omega$, $h_{fe} = 50$, $h_{ic} = 1.1\ \Omega$, $h_{oc} = 25\ \mu A/V$ and $h_{re} = 2.5 \times 10^{-4}$, as shown in Fig.
Approximate H-Model For CE Amplifier

Approximate CE model
Current Gain \[ A_i \approx -h_{fe} \]

Input Impedance \[ R_i \approx h_{ie} \]

Voltage Gain: \[ A_v = \frac{A_i R_L}{R_i} = \frac{A_i R_L}{h_{ie}} \]

Output Impedance \[ Y_o = 0 \]
\[ R_o = \frac{1}{Y_o} = \infty \]
\[ R'_o = R_o \parallel R_L = \infty \parallel R_L = R_L \]
Approximate H-Model For CC Amplifier

Simplified CC model
Current gain: 
\[ A_i = \frac{I_o}{I_b} = -\frac{I_e}{I_b} = 1 + h_{fe} \]

Input resistance:
\[ R_i = \frac{V_b}{I_b} = h_{ie} + (1 + h_{fe}) R_L \]

Voltage gain \( (A_v) \):
\[ A_v = \frac{(1 + h_{fe}) R_L}{h_{ie} + (1 + h_{fe}) R_L} \approx 1 \]

Output resistance \( R_o \):
\[ R_o = \frac{V_o}{I_e} = \frac{R_s + h_{ie}}{1 + h_{fe}} \]

\[ R'_o = R_o \parallel R_L = \infty \parallel R_L = R_L \]
Approximate H-Model For CB Amplifier

Simplified CB model
Current gain \[ A_i = \frac{h_{fe}}{1 + h_{fe}} \]

Input resistance \((R_i)\) \[ R_i = \frac{h_{ie}}{1 + h_{fe}} \]

Voltage gain \((A_v)\) \[ A_v = \frac{h_{fe}}{1 + h_{fe}} \times R_L = \frac{h_{fe} R_L}{h_{ie}} \]

Output resistance \((R_o)\) \[ R_o = \left. \frac{V_o}{I_c} \right|_{V_s=0} \]

\[ R'_o = R_o \parallel R_L = \infty \parallel R_L = R_L \]
Design Problem

For the circuit shown in Fig. estimate $A_v$, $A_i$, $R_i$ and $R_o$ using reasonable approximations. The $h$-parameters for the transistor are given as

\begin{align*}
h_{fe} &= 100 \quad h_{ie} = 2000 \, \Omega \quad h_{re} \text{ is negligible} \quad \text{and} \quad h_{oe} = 10^{-5} \, \text{mhos (U)}. \\
I_b &= 100 \, \mu A.
\end{align*}
Miller’s Theorem

Hillers theorem is used to simplify the analysis of a circuit whenever there is a feedback connection in the circuit.

\[ Z_1 = \frac{Z}{1 - K} \]

\[ Z_2 = \frac{Z \cdot K}{K - 1} \]
Analysis of Common Emitter Amplifier with Collector to Base Bias
AC equivalent circuit
Design Problems

The Fig. shows a common emitter amplifier with collector to base bias. Calculate $R_i$, $R'_i$, $A_v$, $A_{vs}$, $A_i$. The transistor parameters are $h_{ie} = 1.1 \, \text{K}$, $h_{fe} = 50$, $h_{oc} = 25 \times 10^{-6} \, \text{A/V}$, $h_{re} = 2.5 \times 10^{-4}$. 

![Circuit Diagram]
Design Problems

For a Common Emitter Configuration, what is the maximum value of $R_L$ for which $R_1$ differs by not more than 10% of its value at $R_2 = 0$?

$$h_{ie} = 1100 \Omega; \quad h_{fe} = 50$$

$$h_{re} = 2.50 \times 10^{-4}; \quad h_{oe} = 25 \mu A/V$$
Analysis Of CE Amplifier With Unbypassed $R_E$

- $R_E$ is added to stabilize the gain of the amplifier
- $R_E$ acts as a feedback resistor
- The overall gain will reduce with unbypassed $R_E$
AC Equivalent Circuit For CE Amplifier with Unbypassed $R_E$
AC Equivalent Circuit For CE Amplifier with $R_E$ Splitted using dual of Miller’s Theorem
h-Parameter Equivalent Circuit
(Exact Analysis)

\[
A_i = \frac{-h_{fe}}{1 + h_{re}R'_L} = \frac{-h_{fe}}{1 + h_{oe}\left(R_L + \frac{A_i - 1}{A_i}R_E\right)}
\]
h-Parameter Equivalent Circuit
(Approximate Analysis)

Approximate model for CE amplifier with $R_E$
Current gain \[ A_i = \frac{-I_c}{I_b} = \frac{-h_{fe}I_b}{I_b} = -h_{fe} \]

Input resistance \[ R_i = \frac{V_i}{I_b} = h_{ie} + (1 + h_{fe}) R_E \]

Voltage gain \[ A_v = \frac{A_i R_L}{R_i} = \frac{-h_{fe} R_L}{h_{ie} + (1 + h_{fe}) R_E} \]

Output resistance \[ R_o = \frac{V_o}{I_o} \bigg|_{V_s=0} \]

\[ R_o' = R_o \parallel R_L = \infty \parallel R_L = R_L \]
**Example** Fig. shows a single stage CE amplifier with unbypassed emitter resistance find current gain, input resistance, voltage gain and output resistance. Use typical values of $h$-parameter.
MULTISTAGE AMPLIFIERS
Need For Cascading

- When the amplification of a single stage amplifier is not sufficient, or,
- When the input or output impedance is not of the correct magnitude, for a particular application two or more amplifier stages are connected, in cascade. Such amplifier, with two or more stages is also known as multistage amplifier.
Block diagram of 2-Stage Cascade Amplifier

Gain of 2-Stage Cascade Amplifier
$$G_1 = \frac{P_2}{P_1} \quad ; \quad G_2 = \frac{P_3}{P_2}$$

Overall gain

$$G = \frac{P_3}{P_1}$$

$$= \frac{P_2}{P_1} \cdot \frac{P_3}{P_2}$$

$$G = G_1 \cdot G_2$$

Decibel Voltage Gain

Cascaded Stages

![Cascaded Stages Diagram](image)

**Fig. 2.23** Cascaded stages

$$A = A_1 \times A_2$$

$$A_1 = A_1' + A_2' \text{, (in decibels)}$$
Methods of Inter Stage Coupling

In multistage amplifier, the output signal of preceding stage is to be coupled to the input circuit of succeeding stage. For this interstage coupling, different types of coupling elements can be employed. These are:

1. RC coupling
2. Transformer coupling
3. Direct coupling
Two stage RC coupled amplifier using transistors
Two stage transformer coupled amplifier using transistors
Two stage directly coupled amplifier using transistors
Frequency Response of 2-Stage RC Coupled Amplifier
## Comparison Between Coupling Method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RC Coupled</th>
<th>Transformer Coupled</th>
<th>Direct Coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling Components</td>
<td>Resistor and Capacitor</td>
<td>Impedance matching transformer</td>
<td>–</td>
</tr>
<tr>
<td>Block DC</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Frequency response</td>
<td>Flat at middle frequencies</td>
<td>Not uniform, high at resonant frequency and low at other frequencies</td>
<td>Flat at middle frequencies and improvement in the low frequency response</td>
</tr>
<tr>
<td>Impedance matching</td>
<td>Not achieved</td>
<td>Achieved</td>
<td>Not achieved</td>
</tr>
<tr>
<td>DC amplification</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Weight</td>
<td>Light</td>
<td>Bulky and heavy</td>
<td></td>
</tr>
<tr>
<td>Drift</td>
<td>Not present</td>
<td>Not present</td>
<td>Present</td>
</tr>
<tr>
<td>Hum</td>
<td>Not present</td>
<td>Present</td>
<td>Not present</td>
</tr>
<tr>
<td>Application</td>
<td>Used in all audio small signal amplifiers. Used in record players, tape recorders, public address systems, radio receivers and television receivers.</td>
<td>Used in amplifier where impedance matching is an important criteria. Used in the output stage of the public address system to match the impedance of loudspeaker. Used in the RF amplifier stage of the receiver as a tuned voltage amplifier.</td>
<td>Used in amplification of slow varying parameters and where DC amplification is required.</td>
</tr>
</tbody>
</table>
CE-CE Cascade Amplifier
h-parameter equivalent circuit for CE-CE cascade amplifier
Cascode Amplifier
AC equivalent circuit

\[ R_B = R_3 \parallel R_4 \]

\[ V_o \]

\[ V_i \]

\[ I_{e1} \]

\[ I_{c1} \]

\[ I_{e2} \]

\[ I_{c2} \]

\[ R_s \]

\[ V_s \]

\[ R_i' \]

\[ R_i \]
h-parameter equivalent circuit for cascode amplifier
h-parameter equivalent circuit when output shorted
h-parameter equivalent circuit when $I_b = 0$
CE-CC Amplifier

Analysis for first stage
Darlington Transistors
AC Equivalent Circuit:

\[
\begin{align*}
B & \quad h_{ie} \quad I_b \quad E \\
C & \quad h_{fe} I_b \quad R_E \\
E & \\
B_1 & \quad h_{ie} \quad I_{b1} \\
C_1 & \quad h_{fe} I_{b1} \quad V_{ce1} \\
E_1 & \quad h_{oe} V_{ce1} \\
R_{L1} & = (1 + h_{fe}) R_E
\end{align*}
\]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single stage</th>
<th>Darlington</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Resistance</td>
<td>$R_i = (1 + h_{fe}) R_E = 168.3 , \text{k}, \Omega$</td>
<td>$R_i = \frac{(1 + h_{fe})^2 R_E}{1 + h_{oe} (1 + h_{fe}) R_E} \approx 1.65 , \text{M}, \Omega$</td>
</tr>
<tr>
<td>Current Gain</td>
<td>$A_i = 1 + h_{fe} = 51$</td>
<td>$A_i = \frac{(1 + h_{fe})^2}{1 + h_{oe} (1 + h_{fe}) R_E} \approx 500$</td>
</tr>
</tbody>
</table>
Bootstrap Emitter Follower

\[ R_{M1} = \frac{R_3}{1-A_v} \]
\[ R_{M2} = \frac{R_3A_v}{A_v-1} \]
Bootstrapped Darlington circuit
AC Equivalent circuit for bootstrapped Darlington circuit

(a) 

(b) 

(c) 

(d)
Bootstrapped Darlington Circuit Alternative Approach

AC equivalent circuit
Bootstrapped Darlington Circuit Alternative Approach
AC equivalent circuit
Frequency Response of an RC Coupled Amplifier

Bandwidth of an Amplifier

Frequency response, half power frequencies and bandwidth of an RC coupled amplifier
Hybrid – π Common Emitter Transconductance Model
UNIT-III

Feedback Amplifiers & Oscillators
CLASSIFICATION OF AMPLIFIERS

• Amplifiers can be classified broadly as,
• 1. Voltage amplifiers.
• 2. Current amplifiers.
• 3. Transconductance amplifiers.
• 4. Transresistance amplifiers.
VOLTAGE AMPLIFIER

This circuit is a 2-port network and it represents an amplifier (see in Fig 7.1). Suppose $R_i \gg R_s$, drop across $R_s$ is very small.

*Equivalent circuit of voltage amplifiers.*
CURRENT AMPLIFIER

- An ideal current amplifier is one which gives output current proportional to input current and
- the proportionality factor is independent of $R_s$ and $R_L$. 
TRANSCONDUCTANCE AMPLIFIER

Ideal Transconductance amplifier supplies output current which is proportional to input voltage independently of the magnitude of Rs and RL.
TRANS RESISTANCE AMPLIFIER

It gives output voltage $V_o$ proportional to $I_s$, independent of $R_s$ and $R_L$. For ideal amplifiers

$R_j = 0$, $R_o = 0$
Introduction To Feedback

• The process of injecting a fraction of output energy of some device back to the input is known as feedback.

• some of the shortcomings(drawbacks) of the amplifier circuit are:
  1. Change in the value of the gain due to variation in supplying voltage, temperature or due to components.
  2. Distortion in wave-form due to non linearities in the operating characters of the amplifying device.
  3. The amplifier may introduce noise (undesired signals)

• The above drawbacks can be minimizing if we introduce feedback
basic types of feedback in amplifiers

Feedback

Positive (regenerative)

Negative (degenerative)

Voltage

Series

Shunt

Current

Series

Shunt
Positive feedback

• When the feedback energy (voltage or current) is in phase with the input signal and thus aids it, it is called *positive feedback*. 
• *Both amplifier* and feedback network introduce a phase shift of 180°. The result is a 360° phase shift around the loop, causing the *feedback voltage* $V_f$ to be in phase with the input signal $V_{in}$.

![Fig. Block diagram for positive feedback](image-url)
Negative feedback.

• When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called negative feedback.
• The amplifier introduces a phase shift of 180° into the circuit while the feedback network is so designed that it introduces no phase shift (i.e., 0° phase shift).
• Negative feedback is also called as degenerative feedback.

Fig. negative feedback amplifier
CLASSIFICATION OF FEEDBACK AMPLIFIERS

Voltage series feedback.

Voltage shunt Feedback

Current Shunt Feedback

Current Series Feedback
EFFECT OF NEGATIVE FEEDBACK ON TRANSFER GAIN

- REDUCTION IN GAIN

\[
A'_{V} = \frac{A_{V}}{1 + \beta A_{V}} \quad \text{Denominator is } > 1. \quad \therefore \quad A'_{V} < A_{V}
\]
INCREASE IN BANDWIDTH

\[ f_H' = f_H (1 + \beta_v A_{v(mid)}) \]

\[ f_L' = \frac{f_L}{1 + \beta_v A_{v(mid)}} \]

REDUCTION IN DISTORTION

\[ \frac{D}{1 + \beta_v A_v} \text{ is } < D \]
- FEEDBACK TO IMPROVE SENSITIVITY
- FREQUENCY DISTORTION
- BAND WIDTH

\[(BW)_f = (1 + \beta A_m) \cdot BW\]
- **SENSITIVITY OF TRANSISTOR GAIN**

\[
\text{Sensitivity} = \frac{\frac{dA_f}{A_f}}{\frac{dA}{A}}
\]

- **REDUCTION OF NONLINEAR DISTORTION**

\[
B_{2f} = \frac{B_2}{1 + \beta A} \quad B_{2f} < B_2
\]
REDUCTION OF NOISE

\[ N_F = \frac{N}{1 + \beta A} \]

\[ N_F < N. \text{ Noise is reduced with negative feedback.} \]

TRANSFER GAIN WITH FEEDBACK

Consider the generalized feedback amplifier

![Feedback Amplifier Diagram]

- **Comparator mixer**
- **Input signal** \( X_S \)
- **Difference signal** \( X_d = X_i \)
- **Basic Amplifier** \( A \)
- **Feedback signal** \( X_f = \beta X_0 \)
- **Output signal** \( X_0 = AX_i \)
- **External load** \( R_L \)
Return Ratio
\[ \beta A = \text{Product of feedback factor } \beta \text{ and amplification factor } A \text{ is called as Return Ratio.} \]

Return Difference \((D)\)
The difference between unity \((1)\) and return ratio is called as Return difference.

\[ D = 1 - (\beta A) = 1 + \beta A. \]
CLASSIFICATION OF FEEDBACK AMPLIFIERS

There are four types of feedback,

1. Voltage series feedback.
2. Voltage shunt feedback.
3. Current shunt feedback.
4. Current series feedback

\[ V_{i} \rightarrow A \rightarrow V_{o} \rightarrow R_{L} \]

\[ V_{i} \rightarrow A \rightarrow V_{o} \rightarrow R_{L} \]

Voltage series feedback. Voltage shunt Feedback
EFFECT OF FEEDBACK ON INPUT RESISTANCE

Voltage shunt Feedback

\[ R'_i = \frac{R_i}{(1 + \beta_i A_i)} \]

Current Shunt Feedback

\[ R_{if} = \frac{V_i}{(1 + \beta A_i) I_i} = \frac{R_i}{1 + \beta A_i} \]
voltage series feedback.

\[ R_{if} = R_i (1 + \beta A) \]

Current Series Feedback

\[ R_{if} = R_i \left(1 + \beta \frac{V_o}{V_1}\right) = R_i (1 + \beta A_v) \]

EFFECT OF NEGATIVE FEEDBACK ON Ro

voltage series feedback.

\[
R_{of} = \frac{R_o x R_L}{1 + \beta A_v} = \frac{R_o R_L}{R_o + R_L + \beta A_v R_L}
\]

Current Shunt Feedback

\[
R_{of} = R_0 (1 + \beta A_i)
\]
ANALYSIS OF FEEDBACK AMPLIFIERS

Block Schematic
Current shunt feedback.

Equivalent circuit.
CURRENT SERIES FEEDBACK

VOLTAGE SHUNT FEEDBACK
OSCILLATORS

Oscillator is a source of AC voltage or current.
Oscillator Circuit

- Oscillator is an electronic circuit which converts dc signal into ac signal.

- Oscillator is basically a positive feedback amplifier with unity loop gain.

- For an inverting amplifier- feedback network provides a phase shift of $180^\circ$ while for non-inverting amplifier- feedback network provides a phase shift of $0^\circ$ to get positive feedback.

$$\frac{V_o}{V_s} = \frac{A}{1 - A\beta}$$

If $\beta A=1$ then $V_o = \infty$; Very high output with zero input.

Use positive feedback through frequency-selective feedback network to ensure sustained oscillation at $\omega_0$.

Use of Oscillator Circuits

- Clock input for CPU, DSP chips ...
- Local oscillator for radio receivers, mobile receivers, etc
- As a signal generators in the lab
- Clock input for analog-digital and digital-analog converters
Oscillators

- If the feedback signal is not positive and gain is less than unity, oscillations dampen out.
- If the gain is higher than unity then oscillation saturates.

Type of Oscillators

Oscillators can be categorized according to the types of feedback network used:

- RC Oscillators: Phase shift and Wien Bridge Oscillators
- LC Oscillators: Colpitt and Hartley Oscillators
- Crystal Oscillators
There are two types of oscillators circuits:

1. Harmonic Oscillators
2. Relaxation Oscillators

PERFORMANCE MEASURES OF OSCILLATOR CIRCUITS:

- Stability:
- Amplitude stability:
- Output Power:
- Harmonics:
Total phase shift = 360° (180° + 180°). Therefore, to get sustained oscillations,

1. The loop gain must be unit 1.

2. Total Loop phase shift must be 0° or 360°. (Amplifier circuit produces 180° phase shift and feedback network another 180°.)

SINUSOIDAL OSCILLATORS

Block schematic
BARKHAUSEN CRITERION

$|\beta A| = 1$ and phase of $-A\beta = 0$. 
R - C PHASE-SHIFT OSCILLATOR

Transistor phase shift oscillator.

\[ h_{fe} K > 4K^2 + 23K + 29 \quad \text{K} < 2.7 \]

\[ h_{fe} > 4K + 23 + \frac{29}{K} \quad h_{fe} > 44.5 \]
A GENERAL FORM OF LC OSCILLATOR CIRCUIT

(a) 

(b)
- $\alpha \beta$ must be positive, and at least unity in magnitude. Then $X_1$ and $X_2$ must have the same sign.

\[-\alpha \beta = \frac{A_V X_1}{X_2}.
\]

So if $X_1$ and $X_2$ are capacitive, $X_3$ should be inductive and vice versa.

If $X_1$ and $X_2$ are capacitors, the circuit is called Colpitts Oscillator
If $X_1$ and $X_2$ are inductors, the circuit is called Hartley Oscillators
(a) Colpitts oscillator

\[ f = \frac{1}{2\pi\sqrt{LC_T}} \]

where \[ C_T = \frac{C_1C_2}{C_1+C_2} \]

(b) Hartely oscillator circuit

\[ f = \frac{1}{2\pi\sqrt{(L_1+L_2)C_3}} \]
Wien bridge oscillator circuit.

Lead Network: \[ I \rightarrow C \rightarrow R \rightarrow V \rightarrow I \]
- Same \( I \) is passing through \( C \) and \( R \).
- So \( I \) leads \( V \).

Lag Network: \[ I \rightarrow C \rightarrow R \]
- \( I \) lags with respect to \( V \).
Wien Bridge oscillator circuit.

\[ f = \frac{1}{2\pi RC} \]

\[ h_{fe} = 4k + 23 + \frac{29}{K} \]
CRYSTAL OSCILLATORS

Crystal

Electrical Model

\[ f = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{R^2}{L^2}} \]
Transistor Audio Power Amplifier

- A transistor amplifier which raises the power level of the signals that have audio frequency range is known as **transistor audio power amplifier**.

- A transistor that is suitable for power amplification is generally called a **power transistor**.

- The typical power output rating of a power amplifier is 1W or more.
Factors to be considered in large signal amplifiers:

- Output power
- Distortion
- Operating region
- Thermal considerations
- Efficiency ($\eta$)
block diagram of an audio amplifier
## Difference Between Voltage and Power Amplifiers

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Particular</th>
<th>Voltage amplifier</th>
<th>Power amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\beta$</td>
<td>High ($&gt; 100$)</td>
<td>low (5 to 20)</td>
</tr>
<tr>
<td>2.</td>
<td>$R_c$</td>
<td>High (4 – 10 kΩ)</td>
<td>low (5 to 20 Ω)</td>
</tr>
<tr>
<td>3.</td>
<td>Coupling</td>
<td>usually $R – C$ coupling</td>
<td>Invariably transformer coupling</td>
</tr>
<tr>
<td>4.</td>
<td>Input voltage</td>
<td>low (a few mV)</td>
<td>High (2 – 4 V)</td>
</tr>
<tr>
<td>5.</td>
<td>Collector current</td>
<td>low (≈ 1 mA)</td>
<td>High (&gt; 100 mA)</td>
</tr>
<tr>
<td>6.</td>
<td>Power output</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>7.</td>
<td>Output impedance</td>
<td>High (≈ 12 kΩ)</td>
<td>low (200 Ω)</td>
</tr>
</tbody>
</table>
Performance Quantities of Power Amplifiers

(i) Collector efficiency

The ratio of a.c. output power to the zero signal power (i.e. d.c. power) supplied by the battery of a power amplifier is known as collector efficiency.

(ii) Distortion

The change of output wave shape from the input wave shape of an amplifier is known as distortion.

(iii) Power dissipation capability

The ability of a power transistor to dissipate heat is known as power dissipation capability.
Classification of Power Amplifiers

• Class A: It is one, in which the active device conducts for the full 360°.
• Class B: Conduction for 180°.
• Class C: Conduction for < 180°.
• Class AB: Conduction angle is between 180° and 360°.
• Class D: These are used in transmitters because their efficiency is high: 100%.
• Class S: Switching regulators are based on class 'S' operation.
Class A power amplifier

• If the collector current flows at all times during the full cycle of the signal, the power amplifier is known as **class A power amplifier**.

• If the Q point is placed near the centre of the linear region on the dynamic curve, class A operation results. Because the transistor will conduct for the complete 360°, distortion is low for small signals and conversion efficiency is low.
Types of class-A power Amplifiers

1. Series fed
   There is no transformer in the circuit. RL is in series with V cc. There is DC power drop across RL. Therefore efficiency = 25% (maximum).

2. Transformer coupled
   • The load is coupled through a transformer. DC drop across the primary of the transformer is negligible. There is no DC drop across RL. Therefore efficiency = 50% maximum.
Series Fed class-A power Amplifier

Fig. (a) Series fed Class A power amplifier circuit

Fig. (b) Transistor curve
Transformer Coupled class-A power Amplifier

Fig.(a) Transformer Coupled Class A power amplifier circuit

Fig.(b) Transfer curve
Important Points About Class A Power Amplifier

• A transformer coupled class A power amplifier has a maximum collector efficiency of 50%.

• The power dissipated by a transistor is given by:
  \[ P_{\text{dis}} = P_{\text{dc}} - P_{\text{ac}} \]

• When no signal is applied to a class A power amplifier, \( P_{\text{ac}} = 0 \).
  \[ \therefore P_{\text{dis}} = P_{\text{dc}} \]

• When a class A power amplifier is used in the final stage, it is called single ended class A power amplifier.
Class B power amplifier

- If the collector current flows only during the positive half-cycle of the input signal, it is called a **class B power amplifier**.

- For class B operation the Q point is set near cutoff. So output power will be more and conversion efficiency is more. Conduction is only for 180

Transfer curve
Types of class-B power Amplifiers

- **Push-Pull Amplifier**
  The standard class B push-pull amplifier requires a centre tapped transformer

- **Complimentary Symmetry Circuits (Transformer Less Class B Power Amplifier)**
  Complementary symmetry circuits need only one phase
  They don't require a centre tapped transformer.
Advantages & Disadvantages of Class B power Amplifier

Advantages
1. More output power; efficiency = 78.5%. Max.
2. Efficiency is higher. Since the transistor conducts only for 180°, when it is not conducting, it will not draw DC current.
3. Negligible power loss at no signal.

Disadvantages:
1. Supply voltage V cc should have good regulation. Since if V cc changes, the operating point changes (Since Ic changes). Therefore transistor may not be at cut off.
2. Harmonic distortion is higher. (This can be minimized by pushpull connection).
Class B Push-Pull Amplifier

Push Pull amplifier circuit

\[ V_{CE} = \frac{V_{CC}}{2} \]

\[ V_{CC} = I_{C(sat)} \]

AC load line

Q-point

\[ V_{CE} \]
Complimentary Symmetry Circuits (Transformer Less Class B Power Amplifier)

Fig. Complimentary Symmetry circuit
Advantages & Disadvantages of Class B Complementary Power Amplifier

• **Advantages**
  (i) This circuit does not require transformer. This saves on weight and cost.
  (ii) Equal and opposite input signal voltages are not required.

• **Disadvantages**
  (i) It is difficult to get a pair of transistors (npn and pnp) that have similar characteristics.
  (ii) We require both positive and negative supply voltages.
Differences between class-A & B power Amplifiers

<table>
<thead>
<tr>
<th>Class A</th>
<th>Class B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less power</td>
<td>More power</td>
</tr>
<tr>
<td>Lesser $\eta$</td>
<td>More $\eta$ upto 78.5%</td>
</tr>
<tr>
<td>Less Harmonic distortion</td>
<td>Harmonic distortion is more</td>
</tr>
</tbody>
</table>
Heat Sinks

• The metal sheet that serves to dissipate the additional heat from the power transistor is known as **heat sink**.
• The purpose of heat sinks is to keep the operating temperature of the transistor low, to prevent thermal breakdown.
• Almost the entire heat in a transistor is produced at the collector-base junction. If the temperature exceeds the permissible limit, this junction is destroyed and the transistor is rendered useless.
• Most of power is dissipated at the collector-base junction. This is because collector-base voltage is much greater than the base-emitter voltage, although currents through the two junctions are almost the same.
Mathematical Analysis Of Heat Sinks

\[ \theta_{ja} = \theta_{jc} + \theta_{cn} + \theta_{na} \]
\[ \theta_{jc} = \frac{(T_j - T_c)}{P} \]
\[ \theta_{cs} = \frac{(T_c - T_s)}{P} \]
\[ \theta_{sa} = \frac{(T_s - T_a)}{P} \]

\[ \theta_{ja} = \text{Junction to ambient thermal resistance} \]
\[ \theta_{jc} = \text{Junction to casing thermal resistance} \]
\[ \theta_{cs} = \text{Casing to heat sink thermal resistance} \]
\[ \theta_{sa} = \text{Heat sink to ambient thermal resistance} \]
\[ T_j = \text{Average junction temperature} \]
\[ T_c = \text{Average case temperature} \]
\[ T_s = \text{Average heat sink temperature} \]
\[ T_a = \text{Ambient temperature} \]
\[ P = \text{Power dissipated in Watts.} \]
Classification of heat Sinks

1. Low Power Transistor Type.

2. High Power Transistor Type.
Low Power Transistor Type.

- Low Power Transistors can be mounted directly on the metal chassis to increase the heat dissipation capability. The casing of the transistor must be insulated from the metal chassis to prevent shorting.
- Beryllium oxide insulating washers are used for insulating casing from the chassis. They have good thermal conductivity.
- Zinc oxide film silicon compound between washer and chassis, improves the heat transfer from the semiconductor device to case to the chassis.
High Power Transistor Type.

- re TO-3 and TO-66 types. These are diamond shaped. For power transistors, usually, the ease itself in the collector convention and radiation.
- Finned aluminium heat sinks yield the best heat transfer per unit cost.
Alternate Methods to prevent Thermal breakdown

- It should be realized that the use of heat sink alone may not be sufficient to prevent thermal runaway under all conditions. In designing a transistor circuit, consideration should also be given to the choice of

  (i) operating point

  (ii) ambient temperatures which are likely to be encountered and

  (iii) the type of transistor e.g. metal case transistors are more readily cooled by conduction than plastic ones.
Tuned Amplifiers

• Amplifiers which amplify a specific frequency or narrow band of frequencies are called tuned amplifiers.

• Tuned amplifiers are mostly used for the amplification of high or radio frequencies.

• It offers a very high impedance at resonant frequency and very small impedance at all other frequencies.
Advantages of Tuned Amplifiers

1. Small power loss.
2. High selectivity
3. Smaller collector supply voltage
4. Used in RF amplifiers, Communication receivers, Radar, Television, I.F amplifiers
5. Harmonic distortion is very small
Why not Tuned Circuits for Low Frequency Amplification?

- *Low frequencies are never single*
- *High values of L and C.*
Classification

**Tuned Amplifiers**

- **Small Signal**
  - To amplify low RF signals
  - Power output is low
  - Operated in class A
    - Single tuned
    - Double tuned
    - Staggered tuned

- **Large Signal**
  - To amplify large RF signals
  - Power output is more
  - Operated in class B, class C or class AB modes.
  - Pushpull configuration used to further reduce harmonic distortion.
Single Tuned Amplifier

• Uses one parallel tuned circuit as the load IZI in each stage and all these tuned circuits in different stages are tuned to the same frequency. To get large Av or Ap, multistage amplifiers are used. But each stage is tuned to the same frequency, one tuned circuit in one stage.

Single tuned amplifiers are further classified as:

- Capacitive coupled
- Transformer coupled or inductive coupled
Single Tuned Capacitive Coupled Amplifier
Equivalent circuit of Single Tuned Capacitive Coupled Amplifier
Equivalent circuit of Single Tuned Capacitive Coupled Amplifier (applying Miller's Theorem)
Simplified equivalent circuit
Simplified output circuit
Tapped Single Tuned Capacitance Coupled Amplifier
Equivalent Circuit on the Output Side of the I Stage
Equivalent circuit of Tapped Single Tuned Capacitance Coupled Amplifier
Equivalent circuit after simplification
Single Tuned Transformer Coupled or Inductively Coupled Amplifier

Inductive coupled amplifier circuit (a) and its equivalent (b)
Single Tuned Transformer Coupled or Inductively Coupled Amplifier

(a) Equivalent circuit

(b) Simplified circuit

© Equivalent circuit
Double Tuned Amplifier

- It uses two inductively coupled tuned circuits, for each stage of the amplifier. Both the tuned circuits are tuned to the same frequency, two tuned circuits in one stage, to get sharp response.
- It provides larger 3-db band width than the single tuned amplifier. Therefore Gain x Bandwidth product is more.
- It provides gain - frequency curve having steeper sides and flatter top.
Double tuned amplifier circuit
Double tuned amplifier Equivalent circuit

(a) Equivalent circuit

(b) Modified circuit
Stagger Tuned Amplifier

• This circuit uses number of single tuned stages in cascade. The successive tuned circuits are tuned to slightly different frequencies.

Variation of Av with f
Stability Considerations

• Thermal Effects

• Bias Considerations: Distortion in Audio amplifiers and other types of circuits depends on:
  (i) Input signal level (in mv)
  (ii) Source Resistance
  (iii) Bias Conditions
  (iv) Type of output load and its impedance
  (v) Loading effect.
Relation between hybrid-$\pi$ and $h$-parameters

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Parameter Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$g_m = \frac{I_c}{V_T}$</td>
</tr>
<tr>
<td>2</td>
<td>$r_{bc} = \frac{h_{re}}{g_m}$</td>
</tr>
<tr>
<td>3</td>
<td>$r_{bb'} = h_{le} - r_{bc}$</td>
</tr>
<tr>
<td>4</td>
<td>$r_{bc} = \frac{r_{y'e}}{h_{re}}$</td>
</tr>
<tr>
<td>5</td>
<td>$g_{ce} = \frac{1}{r_{ce}} = h_{oe} - g_{bc} \cdot h_{fe}$</td>
</tr>
</tbody>
</table>
Hybrid - n Parameter Values

Typical values of the hybrid-π parameter at $I_C = 1.3$ mA are as follows:

- $g_m = 50$ mA/V
- $r_{bb'} = 100$ $\Omega$
- $r_{b'e} = 1$ k$\Omega$
- $r_{ce} = 80$ k$\Omega$
- $C_c = 3$ pf
- $C_e = 100$ pf
- $r_{b'c} = 4$ M$\Omega$

*These values depend upon:*

1. Temperature  
2. Value of $I_C$
The Hybrid-\(\pi\) Capacitances

\[ C_e = C_{De} + C_{Te} \approx C_{De} \]

\[ Q_B = \frac{1}{2} \ p'(0) \ A \ W \ q \]

\[ I = -Aq \ D_B \frac{dp'}{dx} \]

\[ = Aq \ D_B \ \frac{p'(0)}{W} \]

Combining equations (1) and (2) we get

\[ Q_B = \frac{IW^2}{2D_B} \]

\[ C_{De} = \frac{dQ_B}{dV} = \frac{W^2}{2D_B} \frac{dI}{dV} \]

\[ = \frac{W^2}{2D_B} \ \frac{I}{r_e} \]

\[ r_e = dV/dI = V_T/I_E \] is the emitter junction incremental resistance.
$$C_{De} = \frac{W^2 I_E}{2 D_B VT}$$

$$= \frac{g_m W^2}{2 D_B}$$

$$C_e \approx \frac{g_m}{2\pi f_T}$$

**CE Short-Circuit Current Gain using Hybrid \( \pi \) Model**

![Hybrid π Model Diagram]

The hybrid-\( \pi \) circuit for a single transistor with a resistive load \( R_L \)

![Simplified Hybrid π Model Diagram]

Simplified hybrid-\( \pi \) model for short circuit CE transistor
Substrate connection.
(a) Simple PMOS device, (b) PMOS inside an $n$-well.
MOS symbols.

(a)  

(b)  

(c)
(a) A MOSFET driven by a gate voltage, (b) formation of depletion region, (c) onset of inversion, (d) formation of inversion layer.

\[ V_{TH} = \Phi_{MS} + 2\Phi_F + \frac{Q_{dep}}{C_{ox}}, \]
Implantation of $p^+$ dopants to alter the threshold.

Formation of inversion layer in a PFET.
Derivation of I/V Characteristics

\[ I = Q_d \cdot v. \]

(a) A semiconductor bar carrying a current \( I \), (b) snapshots of the carriers one second apart.
Channel charge with (a) equal source and drain voltages, (b) unequal source and drain voltages.

\[ I_D = W C_{ox} [V_{GS} - V(x) - V_{TH}] \mu_n \frac{dV(x)}{dx}, \]
Drain current versus drain-source voltage in the triode region.

\[ I_{D,max} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2. \]

\[ I_D \approx \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) V_{DS}, \]

\[ R_{on} = \frac{1}{\frac{W}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}}. \]
Linear operation in deep triode region.

With the condition $V_{DS} \ll 2(V_{GS} - V_{TH})$, we say the device operates in deep triode region.
Saturation of drain current.

Pinch-off behavior.

\[ V(x_1) = V_{GS} - V_{TH} \]

\[ V(x_2) = V_{GS} - V_{TH} \]
\[ I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L'} (V_{GS} - V_{TH})^2, \]

\[ I_D = -\mu_p C_{ox} \frac{W}{L} \left[ (V_{GS} - V_{TH})V_{DS} - \frac{1}{2} V_{DS}^2 \right] \]

\[ I_D = -\frac{1}{2} \mu_p C_{ox} \frac{W}{L'} (V_{GS} - V_{TH})^2. \]

Saturated MOSFETs operating as current sources.
\[ g_m = \frac{\partial I_D}{\partial V_{GS}} \bigg|_{V_{DS,\text{const.}}} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH}) \]

\[ g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} = \frac{2I_D}{V_{GS} - V_{TH}}. \]

MOS transconductance as a function of overdrive and drain current.

W/L Constant

W/L Constant

I_D Constant
NMOS device with negative bulk voltage.
Variation of depletion region charge with bulk voltage.

Channel-Length Modulation

\[ I_D \approx \frac{1}{\mu \varepsilon_0 \varepsilon_r} W (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS}), \]

Finite saturation region slope resulting from channel-length modulation.
\[ g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})(1 + \lambda V_{DS}). \]

\[ = \sqrt{\frac{2\mu_n C_{ox} (W/L) I_D}{1 + \lambda V_{DS}}}, \]

**Subthreshold Conduction**

\[ I_D = I_0 \exp \frac{V_{GS}}{\zeta V_T}, \]

MOS subthreshold char-
(a) Basic MOS small-signal model, (b) channel-length modulation represented by a dependent current source, (c) channel-length modulation represented by a resistor, (d) body effect represented by a dependent current source.
\[ r_O = \frac{\partial V_{DS}}{\partial I_D} \]
\[ = \frac{1}{\partial I_D/\partial V_{DS}}. \]
\[ = \frac{1}{\frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 \cdot \lambda} \]
\[ \approx \frac{1}{\lambda I_D}. \]

\[ g_{mh} = g_m \frac{\gamma}{2\sqrt{2\phi_F + V_{SB}}} \]
\[ = \eta g_m, \]
Complete MOS small-signal model.